Chapter 1
Introduction

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Acronyms, Chemical Formulae, and Units

C	carbon
CH_4	methane
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalents
GHG	greenhouse gas
LCA	life cycle assessment
N_2O	nitrous oxide
NMVOC	non-methane volatile organic compounds
USDA	U.S. Department of Agriculture
U.S. EPA	U.S. Environmental Protection Agency

1 Introduction

This report provides a scientific basis and methods for estimating greenhouse gas emissions (GHGs) and sinks from management practices at an entity level (see box 1-1) for a farm, ranch, or forest system. The methods have been developed for U.S. conditions and are considered applicable to agricultural and forestry production systems in the United States. The report covers the following land-use sectors: croplands/grazing lands, managed wetlands, animal production systems, and forestry, along with changes in land use. The report does not provide methods for lands categorized as settlements (e.g., residential and commercial buildings).

Box 1-1. Definition of Entity

An **entity** is defined as all activities occurring on all tracts of land under the ownership and/or management control—now and for the foreseeable future—of a farm, ranch, or forest landowner or manager.

1.1 Overview of GHG Emissions, Sinks, and Fluxes in Agriculture and Forestry

Since the onset of the Industrial Revolution, global atmospheric concentrations of greenhouse gases (GHGs)—including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—have measurably increased. GHGs trap heat in the atmosphere, making the planet warmer. Since 1880, the average global temperature has increased at least 1.1 °C (NASA Earth Observatory, 2022).

Agriculture and forestry practices are both a source and sink of GHGs. Agricultural soils, enteric fermentation from ruminant livestock production, managed livestock manure, wetlands, rice cultivation, and agricultural residue burning all produce GHG emissions. Activities that capture and sequester carbon in biomass, wood products, and soils and remove CO_2 from the atmosphere are called sinks. Mitigation practices can reduce GHG emissions and increase sinks. GHG fluxes are the exchange of GHGs between the atmosphere and the earth via emissions, deposition, or absorption.

Agricultural activities contributed 11 percent of the net total GHG emissions in the United States in 2020 (U.S. EPA, 2022). These activities include N_2O emissions from agricultural soil management, livestock manure management, and field burning of agricultural residues; CH_4 emissions from enteric fermentation, livestock manure management, rice cultivation, and field burning of agricultural residues; and CO_2 emissions from liming and urea fertilization. Of these activities, agricultural soil management, enteric fermentation, and manure management accounted for approximately 90 percent of U.S agriculture sector emissions in 2020 (see figure 1-1). Emissions and sinks associated with cropland cultivation, grassland management, grassland fires, and the conversion of other land uses into cropland are included in the land use, land-use change, and forestry (LULUCF) sector. The LULUCF sector sequestered enough carbon in 2020 to offset about 13 percent of total U.S. GHG emissions (U.S. EPA, 2022).

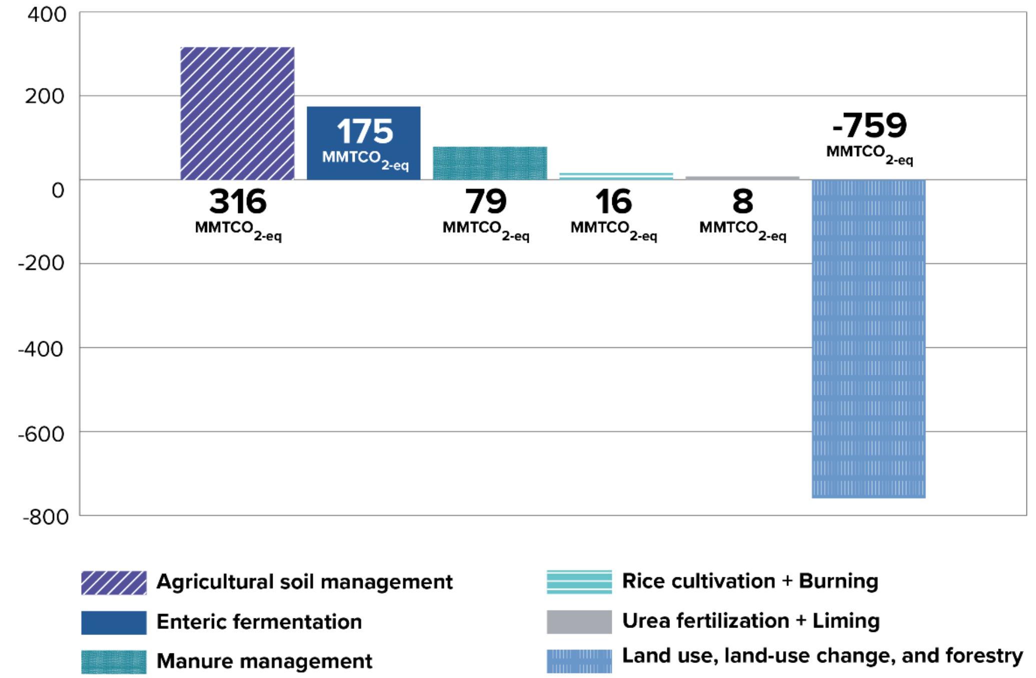

Figure 1-1. Agricultural Net GHG Emissions and Sinks in 2020

Figure 1-2 depicts GHG fluxes from agriculture and forestry systems included in this report. This includes fluxes from croplands and grazing lands (biomass, litter and soil stock changes, rice cultivation, non-flooded soils, urea and liming, biomass burning), animal production (enteric fermentation, manure, and housing), forestry (silviculture, harvested wood products, forest fires, biomass burning, litter/deadwood, litter clearing, urban forest management), and wetlands.

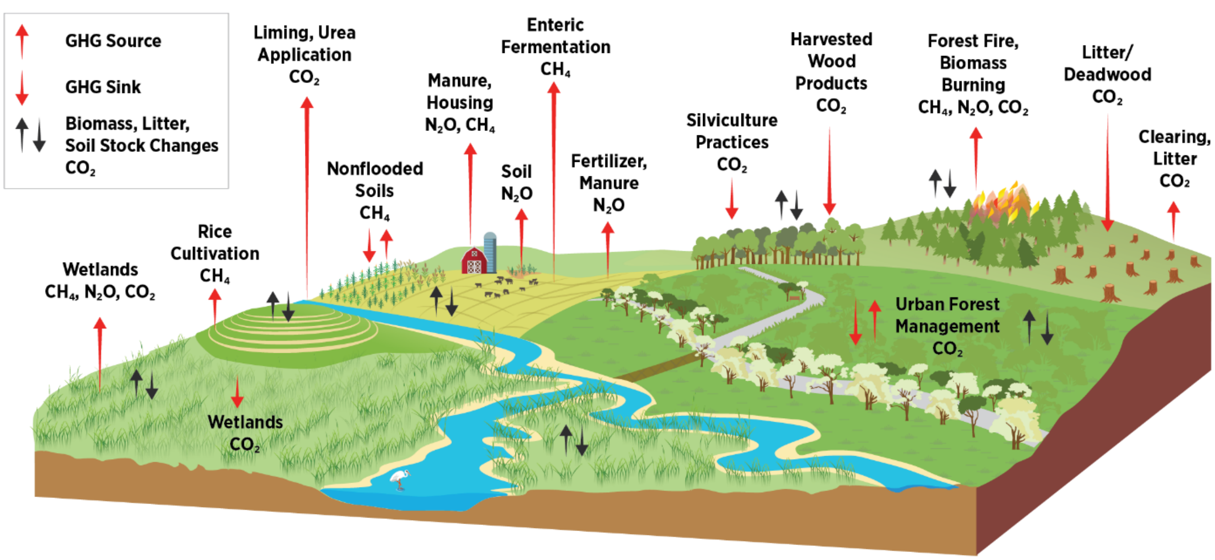

Figure 1-2. The Main GHG Emission Sources and Sinks in Agriculture and Forestry Systems

1.1.1 Report Development Process

In 2008, Section 2709 of the Food, Conservation, and Energy Act directed USDA to "establish technical guidelines that outline science-based methods to measure the environmental service benefits from conservation and land management activities in order to facilitate the participation of farmers, ranchers, and forest landowners in emerging environmental services markets." In response to this legislation, USDA released the first version of this report in 2014, *Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory*.

In 2019, three author teams consisting of 10 to 50 working group members began an update of the 2014 report. All working group members had experience with GHG accounting and/or field research that addressed one or more of the methods needed. Each author team received relevant content from the 2014 report, an outline for the updated report, and a background report (Ogle et al., 2020) summarizing the scientific literature related to the GHG mitigation potential, cost, and feasibility of different management practices.

The review process for this report consisted of:

- **USDA technical review.** USDA's intra-agency review raised a series of comments and questions for the chapter authors. The chapter authors addressed these comments without additional formal meetings.
- **Concurrent interagency and scientific expert technical review.** Once the intra-agency review draft was complete, an interagency group of GHG emissions and inventory experts reviewed the revised draft. The reviewers included individuals from academia, USDA, the U.S. Department of Energy, the U.S. Department of the Interior, the U.S. Environmental Protection Agency (EPA), the U.S. Department of State, and several White House offices. These reviewers were chosen for their recognized expertise, experience in expert reviews, and willingness to participate. This review produced a series of comments and questions for the authors to address.
- **Concurrent Highly Influential Scientific Assessment peer review and public comment period.** Once all the expert comments were addressed, the report was made available for public comment. This review coincided with a final review by USDA and other Federal agency GHG experts. Chapter authors assessed and addressed these comments, and the report was edited for publication.

1.1.2 Changes From the 2014 Report

This report includes updates to the estimation methods to reflect the current state of the science as well as to increase transparency and user friendliness. General rearranging of the chapters occurred, which changed the numbering for several chapters from the 2014 report. Most updates occurred in *Chapter 3: Cropland and Grazing Land Systems*, *Chapter 4: Animal Production Systems*, and *Chapter 5: Managed Forest Systems*. Within these chapters, methods were updated to reflect the most recent science, and efforts were made to streamline the text to make the methods more prominent.

1.1.3 Report Purposes

This report has several important purposes, including the following:

- Enabling landowners and others to accurately estimate GHG fluxes and impacts at an entity scale, including fluxes associated with different management practices.

- Providing methods to help USDA accurately estimate GHG fluxes from current and future conservation programs and practices and assessing the performance of conservation and renewable energy programs. Note that the intensity metrics of GHGs (i.e., emissions per production unit) are not explicitly addressed in this guidance.
- Providing a basis for updating USDA's GHG flux estimation tools, including COMET-Planner and COMET-Farm (see box 1-2).
- Informing GHG estimates for other programs. For example, this report may inform emerging methods that underly voluntary GHG registries, facilitate regional GHG markets, and provide technical inputs for future GHG reporting programs.

Box 1-2. COMET-Planner and COMET-Farm Tools

- COMET-Planner provides generalized estimates of GHG impacts of conservation practices.
- COMET-Farm is a publicly available, user-friendly web-based tool that estimates detailed, farm-specific GHG fluxes. The tool can help users evaluate different options for reducing GHG emissions and sequestering carbon.

Figure 1-3 illustrates how these methods inform practice, technology research, and methods development at national, program, and farm levels. Entity-scale estimates may be scaled up to the program and national level, and have impacts on U.S. Government strategy and the *Inventory of U.S. Greenhouse Gas Emissions and Sinks.*

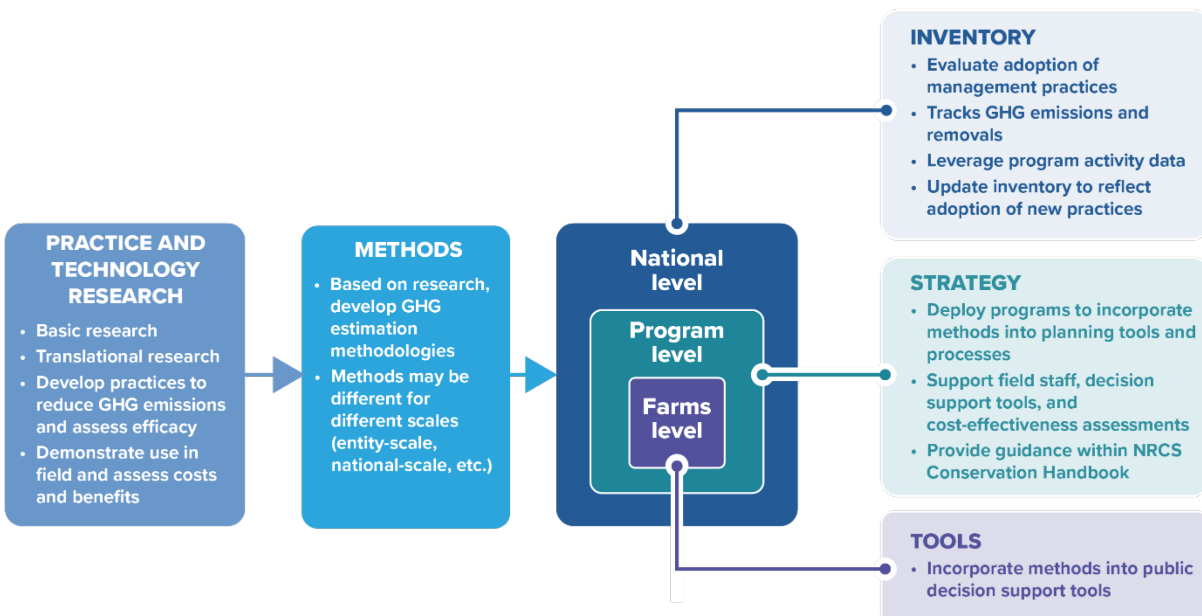

Figure 1-3. Agricultural GHG Estimation Research, Methods, and Applications

In addition, the methods are designed to:

- **Be independent, yet consistent and transparent**. The methods are designed to stand on their own, independent of any other accounting system, yet stay as consistent as possible with other accounting systems. For example, the methods are consistent with the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* where appropriate so that entity-scale data can be compared with the national inventory.
- **Provide flexibility.** The methods are designed to estimate fluxes for the entirety of a farm, ranch, or forest, but are also appropriate for evaluating a single management practice implemented within a single farm, ranch, or forest or aggregated across multiple farms, ranches, or forests. They can also be adapted to county or State levels. The methods are also intended to maintain maximum applicability for potential use in environmental markets.
- **Address practical concerns around GHG estimation.** This includes the risk of reversal if management practices revert in the foreseeable future. (For example, a land manager must understand that a change in management that results in soil carbon sequestration, if reversed, will likely lead to the extra stored carbon being released to the atmosphere.)
- **Display consistency and transparency in reporting.** The methods were intended to facilitate entity-level reporting by a diversity of users with a wide range of technical capacities and data availability.
- **Calculate GHG fluxes over time.** The methods can be used to estimate emissions, sinks, and removals across multiple years, showing changes over time.
- **Allow for integrated estimates.** This report brings estimation approaches from all agriculture and forestry sectors into one report so that an integrated estimate can be derived for all activities within the boundary of a farm, ranch, or forest operation**.**

1.1.4 Appropriate Uses and Limitations of the Report

When using or referencing this report, the following considerations should be kept in mind:

- The report generally does not provide a range of emission/sequestration accounting options at varying levels of complexity (i.e., tiers) for each source category. However, chapter 5 specifies individual options for entities within source categories where there are significant differences in data and/or user familiarity.
- **The methods are not intended to provide a life cycle assessment (LCA).** LCAs evaluate the entire lifespan of a commodity or product to fully quantify its environmental impact. This report focuses on emissions that occur at the entity-scale annually. It does not provide the methods required to quantify upstream production (e.g., animal feed production, fertilizer manufacture) or downstream production (e.g., wastewater treatment, pulp and paper manufacture, or landfills), except for harvested wood product treatment, which is discussed in chapter 5.
- The methods are not meant for estimating emissions from stationary source combustion (e.g., burning heating oil or natural gas to heat animal housing) or mobile source combustion (e.g., fuel use in vehicles), with the exception of chapter 5, which includes emission reductions that occur when substituting woody biomass for nonrenewable energy sources. However, the report does qualitatively discuss obvious changes in combustion levels due to a management practice change. For example, a shift from conventional tillage to no-till can significantly reduce fuel consumption since fewer trips across the field are needed. Methods for quantifying emissions from stationary or mobile combustion sources

are available from other Federal agencies (e.g., EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks*), and a calculator that provides emissions reductions associated with changes in on-farm fuel or electricity use is available at the COMET-Energy website.

1.1.5 Report Contents

The report is intended to be considered in its entirety, with the chapters 1 and 2 providing context for the sector content in chapters 3 through 7 (see box 1-3 for a description of how these chapters are structured). Chapter 8 provides a framework for estimating uncertainty, and the appendixes provide additional technical background, methods documentation, and a discussion of research gaps and other estimation methods.

Box 1-3. Organization of Sector Chapters

Each sector chapter provides:

- Brief background and information on management practices.
- The methods that demonstrate the current best approach to estimating GHG fluxes, balancing the available science and data with the criteria and considerations mentioned previously.
- Discussion of research gaps or priority areas for future data collection that are important to improve the completeness or accuracy of the estimation methods.
- Information about uncertainty and limitations of the methods.

The report is organized as follows:

- **Chapter 1: Introduction.** Describes the objectives of the report, the methods and report development process, and the limitations of the methods presented. Also provides an overview of the sectors covered in the report, and the management practices that influence GHG estimations.
- **Chapter 2: Considerations When Estimating Greenhouse Gas Fluxes from Agriculture and Forestry.** Sets the context for the methods, including linkages and cross-cutting issues that span the sectors, including the definitions of system boundaries. Includes a brief discussion of GHG remote sensing and emissions technologies.
- **Chapter 3: Quantifying Greenhouse Gas Sources and Sinks in Cropland and Grazing Land Systems.** Presents methods for estimating the influence of land use and management practices on GHG emissions (and sinks) in crop and grazing land systems. Methods are described for estimating biomass and soil carbon stocks changes, direct and indirect soil N_2O emissions, methane (CH_4) and N_2O emissions from wetland rice, CH_4 uptake in soils, carbon dioxide (CO_2) emissions or sinks from liming, non-CO_2 GHG emissions from biomass burning, and CO_2 emissions from urea fertilizer application.
- **Chapter 4: Quantifying Greenhouse Gas Sources and Sinks in Animal Production Systems.** Presents enteric fermentation, manure management, and housing methods appropriate for each common livestock sector (i.e., beef, dairy, sheep, swine, and poultry).
- **Chapter 5: Quantifying Greenhouse Gas Sources and Sinks in Managed Forest Systems.** Provides guidance on estimating carbon sequestration and GHG emissions for the forestry sector. Presents an overview of forest carbon accounting elements, including key carbon pool definitions and methods for their estimation. "Levels" are provided for this chapter to allow flexibility for users with ranges of knowledge, available data, and resources.
- **Chapter 6: Quantifying Greenhouse Gas Sources and Sinks in Managed Wetland Systems.** Provides guidance on estimating carbon stock changes, CH_4, and N_2O emissions from actively managed wetlands.

- **Chapter 7: Quantifying Greenhouse Gas Sources and Sinks From Land-Use Change.** Provides guidance on estimating the net GHG flux resulting from changes between land types—i.e., conversions into and out of cropland, wetland, grazing land, or forestland—at the entity scale.
- **Chapter 8: Uncertainty Assessment for Quantifying Greenhouse Gas Sources and Sinks.** Provides a framework for a Monte Carlo assessment of estimation uncertainty.
- **Chapter Appendixes:** Include background technical information, including descriptions of systems, biological processes, general interactions, or emissions generation (or sinks) processes. Provide method documentation, including the rationale for the method, sometimes describing why a method was preferred over another available method, in addition to supplemental technical documentation of chosen methods. Describes current research gaps the authors are aware of and sometimes where there are potential other methods or processes.

1.2 Overview of Sectors, Management Practices, and Estimation Methods

This section provides a brief description of each sector covered in this report, along with their key emissions and sinks. The management practices that affect GHG emissions for each sector are also listed, as well as the chapter to use when estimating GHGs for the sector.

Box 1-4. Definition of Management Practice

For this report, ***management practices*** are defined as activities an entity undertakes that can affect GHG emissions and removals. Examples of management practices include (but are not limited to) irrigation, tillage, and residue management for croplands.

When estimating GHG emissions using the methods in this report, it is important for landowners to provide a complete description of the management practices (see box 1-4) used. This is because the influence of management practices on GHG emissions is not typically the simple sum of each practice's effect. Instead, one practice can influence another. Different variables, such as soil characteristics and weather or climate conditions, also have an impact. For example, the influence of tillage on soil carbon depends on residue management. The influence of nitrogen fertilization rates can depend on fertilizer placement and timing. Note also that trends in GHG emissions associated with a change in management practices can be reversed if the landowner reverts to the original practice.

1.2.1 Croplands and Grazing Lands

Croplands include all systems used to produce food, feed, and fiber commodities, as well as feedstocks for bioenergy production. Most U.S. croplands are drylands (nonwetlands, irrigated or unirrigated); rice and a few other crops are grown in wetlands. Croplands also include agroforestry systems that are a mixture of crops and trees, such as alley cropping, shelterbelts, and riparian woodlots.

Grazing lands are systems used for livestock production and occur primarily on grasslands. Grasslands are composed principally of grasses, grass-like plants, forbs, or shrubs suitable for grazing and browsing; they include both pastures and native rangelands (U.S. EPA, 2022). Other lands (i.e., savannas, some wetlands, tundra) can be considered grazing lands if used for livestock production. Grazing lands include native rangelands as well as pastures that may need periodic management to maintain grass.

Cropland and grazing lands are significant sources of CO_2, N_2O, and CH_4 emissions and can also be a sink for CO_2 (U.S. EPA, 2022). Climate and soil characteristics can impact all GHG fluxes. Land use and management activities, particularly nitrogen application, influence N_2O emissions from soils. Fertilizer rate, timing, and placement, along with nitrogen source, are the main influences on nitrogen use efficiency and N_2O emissions. Land use and management also influence carbon stocks in biomass, dead biomass, and soil pools. Tillage intensity, cropping intensity, and crop rotation can significantly affect soil carbon stocks. Box 1-5 presents other management activities that affect GHG emissions and sinks from croplands and grazing lands.

Box 1-5. Management Practices Affecting GHG Emissions From Croplands and Grazing Lands

- Nutrient management (synthetic and organic)
- Tillage practices
- Crop rotations, cover crops, and cropping intensity
- Water management (i.e., irrigation, drainage)
- Erosion control
- Management of drained wetlands
- Lime amendments
- Residue management
- Set-aside/reserve cropland
- Biochar amendments to soils
- Flooded rice cultivation
- Livestock grazing practices
- Forage options
- Management to address woody plant encroachment
- Windbreaks
- Alley cropping
- Riparian forest buffers

Which Estimation Methods To Use?

Follow the methods in **Chapter 3: Croplands and Grazing Land** if any of the following apply:

- You manage cropland. Delineate the management units where crop production is the primary activity.
- You manage grazing land. Delineate units where grazing is the primary activity.
- You manage orchards, vineyards, or other agroforestry lands. Delineate management units by crop and management practice.

1.2.2 Animal Production

GHG emissions from animal production systems fall into three main categories: enteric fermentation, housing, and manure management.

Enteric fermentation takes place in animal digestive systems, particularly in ruminant animals. CH_4 is formed in the rumen (the first stomach compartment) as microbial fermentation breaks down food. CH_4 can also arise from hindgut fermentation, but at much lower levels. Several diet management practices can modify enteric fermentation estimates (see box 1-6).

Box 1-6. Management Practices Affecting GHG Emissions From Enteric Fermentation

- Composition of the diet
- Level of dry matter intake
- Feed additives

CH_4 is the only GHG of concern in enteric fermentation. Field studies have confirmed that enteric fermentation does not produce N_2O or ammonia (NH_3) (Reynolds et al., 2010). Although animals produce CO_2 through respiration, the annual net CO_2 is assumed to be zero due to plant photosynthesis (IPCC, 2006).

Housing emissions refer to GHG emissions from manure stored within the housing structure (e.g.., under a barn floor). GHG emissions from manure stored in housing are similar to emissions from manure managed in stockpiles. The main solid manure storage and treatment practices are temporary stacks, long-term stockpiles, and composting. The main liquid manure storage and treatment practices are aerobic lagoons, anaerobic lagoons, runoff holding ponds, storage tanks, anaerobic digestion with biogas utilization, and solid-liquid separation.

The treatment and storage of manure in management systems contributes to CH_4 and N_2O emissions. The magnitude of CH_4 and N_2O emissions from animal manure depends largely on environmental conditions. CH_4 is emitted in anaerobic conditions when oxygen is not available for bacteria to decompose manure, such as when manure is stored in ponds, tanks, or pits, as is typical with liquid/slurry flushing systems. Storing solid manure in stacks or dry lots or depositing it on pasture, range, or paddocks tends to result in more aerobic conditions, in which little or no CH_4 will be formed. Other factors that influence CH_4 generation include the ambient temperature, moisture content, residency time, and manure composition (which depends on the diet of the livestock, growth rate, and type of digestive system) (U.S. EPA, 2022).

Similarly, direct N_2O emissions from livestock manure depend on the manure composition (manure includes both feces and urine), the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system (U.S. EPA, 2022). N_2O forms when the manure is first subjected to aerobic conditions where NH_3 and organic nitrogen are converted to nitrites and nitrates (nitrification). If conditions become sufficiently anaerobic, the nitrates and nitrites can be denitrified (reduced to nitrogen oxides and nitrogen gas) (Robertson and Groffman, 2015). N_2O is an intermediate product of both nitrification and denitrification and can be directly emitted from manure as a result of either of these processes. Dry waste handling systems are generally oxygenated but have pockets of anaerobic conditions from decomposition—conditions that are most conducive to the production of N_2O (USDA, 2022).

Some manure management systems can effectively mitigate the release of GHG emissions from livestock manure. Box 1-7 lists several practices that can influence manure management emissions.

Box 1-7. Management Practices Affecting GHG Emissions From Manure Management

- Type of manure storage
  - Liquid or dry
  - Covered or uncovered
  - Aerated
  - Amendments or additives
- Conditions of manure storage
  - Storage time
  - Climate
- Anaerobic digestion

Which Estimation Methods To Use?

Follow the methods in **Chapter 4: Animal Production Systems** if any of the following apply:

- You manage beef cattle (cow-calf, stocker, and feedlot systems), dairy cattle, sheep, swine, or poultry (layers, broilers, and turkeys).
- You collect manure.

Follow the methods in Chapter 3: Cropland and Grazing Land if:

- You apply manure to land.

1.2.3 Forestry

Forest systems represent a significant opportunity to mitigate GHGs through the sequestration and temporary storage of forest carbon stocks. Forests remove CO_2 from the atmosphere through photosynthesis and store carbon in forest biomass (e.g., stems, root, bark, leaves) and soil, and release CO_2 to the atmosphere via the microbial decomposition of biomass (otherwise termed respiration) and/or combustion of biomass. Net forest carbon stocks increase over time when carbon sequestration during photosynthesis exceeds carbon released during respiration and combustion. Other GHGs are also exchanged by forest ecosystems, such as CH_4 from microbial communities in forest soil and N_2O from fertilizer use, nitrogen deposition, and soil organic matter decomposition.

Harvesting forests releases some sequestered carbon to the atmosphere, while harvested wood products (HWPs) contain the remaining carbon. How HWPs are used (e.g., combustion for energy, manufacture of durable wood products, disposal in landfills) determines the rate at which the carbon is returned to the atmosphere.

Many management practices can reduce GHG emissions and/or increase carbon stocks in the forestry sector, including establishing and/or re-establishing forest, maintaining forest stands, and avoiding forest clearing (see box 1-8).

Box 1-8. Management Practices Affecting Net GHG Emissions From Forestry

- Establishing and reestablishing forest
- Maintaining forest stands
- Stand density management
- Site preparation techniques
- Vegetation control
- Planting
- Natural regeneration
- Fertilization
- Selection of rotation length
- Harvesting and utilization techniques
- Fire and fuel load management
- Reducing the risk of emissions from natural disturbances
- Short-rotation woody crops

Which Estimation Methods To Use?

Follow the methods in **Chapter 5: Forestry** if any of the following apply:

- You manage lands for timber production for lumber, pulp, biofuels or other products. Delineate timber management units.
- **You manage trees outside forests or agroforestry.** Delineate management units that consist of trees outside forests

1.2.4 Wetlands

Wetlands are areas that are either periodically or permanently wet or saturated. Wetlands occur across the United States on many landforms, particularly in floodplains and riparian zones, inland lacustrine systems, glaciated outwash, and coastal plains. The National Wetlands Inventory broadly classifies wetlands into five major systems (Cowardin et al., 1979; DESQ, 2015):

- **Marine:** Includes the ocean or estuary coastline to a given jurisdictional limit.
- **Estuarine:** Tidal wetlands with access to freshwater dilution.
- **Riverine:** Wetlands within a channel of water that connects two enclosed bodies of water.
- **Lacustrine:** Open, nonvegetated systems of a large size (>8 hectares).
- **Palustrine:** Small-sized (<8 hectares) nontidal wetlands with emergent vegetation.

These systems are further classified by major vegetative life form. For example, forested wetlands are often classified as palustrine-forested. Similarly, most grassland wetlands are classified as palustrine wetlands with emergent vegetation (e.g., grasses and sedges). Wetlands also vary greatly with respect to groundwater and surface water interactions that directly influence hydroperiod, water chemistry, and soils (Cowardin et al., 1979; Winter et al., 1998). All these factors, along with climate and land-use drivers, influence overall carbon balance and GHG flux.

The degree of water saturation, as well as climate and nutrient availability, largely control GHG emissions from wetlands. CH_4 is the primary emission from wetlands, which is produced by anaerobic soils that characterize wetland systems. In aerobic conditions (which may occur seasonally in upland wetland ecosystems), decomposition releases CO_2; in anaerobic conditions, it releases CH_4. N_2O emissions from wetlands are typically low unless an outside source of nitrogen is entering the wetland.

Management of the water table within a wetland results in lower CH_4 emissions and an increase in CO_2 emissions due to oxidation of soil organic matter and an increase in N_2O emissions in nutrient-rich soil, while the creation or restoration of wetlands reduces soil N_2O and CO_2 emissions, but increases soil CH_4 emissions (IPCC, 2006).

This report mainly focuses on restoration and management practices associated with riverine and palustrine systems in forested, grassland, and riparian ecosystems. Although other major wetland systems (e.g., estuarine) are significant in the global carbon cycle, these systems have received the most attention in terms of implementation of restoration and management practices to conserve wetlands habitats and sustain ecosystems services (Brinson and Eckles, 2011). Wetlands that have been drained for production of a commodity such as annual crops are not considered wetlands in this report.

Grassland and forested wetlands are subject to a wide range of land use and management practices that influence the carbon balance and GHG flux (Faulkner et al., 2011; Gleason et al., 2011). For example, forested wetlands may be subject to silvicultural prescriptions, and grassland wetlands may be grazed, hayed, or directly cultivated. All these manipulations influence the overall GHG flux. Biomass carbon can change significantly with wetland management, particularly in peatlands and forested wetlands, or when wetlands change from forest to lands dominated by grasses and shrubs or open water. Box 1-9 lists the management practices in wetlands that have an influence on GHG emissions or carbon stock changes.

Box 1-9. Management Practices Affecting GHG Fluxes From Wetlands

- Silvicultural water table management
- Forest harvesting systems
- Forest regeneration systems
- Fertilization
- Conversion to open wetland
- Forest type change
- Water quality management
- Wetland management for waterfowl
- Constructed wetlands for wastewater treatment
- Land-use change to wetlands
- Actively restoring wetlands
- Actively restoring scrub-grass wetlands
- Constructing wetlands
- Passive restoration of wetlands

Which Estimation Methods To Use?

Follow the methods in **Chapter 6: Wetlands** if:

- You manage naturally occurring wetlands or restored wetlands on previously converted wetland sites and do *not* cultivate rice. Delineate management units of naturally occurring or restored wetlands.

Follow the methods in **Chapter 3: Croplands and Grazing Land** if:

- You cultivate rice.
- You manage wetlands drained for commodity production.

1.3 Land-Use Change

Converting land parcels from one land-use category to another can significantly affect a parcel's carbon stocks. For example, converting cropland to wetlands or forestland can cause carbon stock gains, while converting forestlands to grazing lands often causes carbon stock losses. In addition, land-use changes can affect soil organic carbon, particularly when land is converted to croplands (Six et al., 2000).

In many cases, the methods for estimating contributions to the GHG flux resulting from land-use change are the same as those used to estimate carbon stock changes in the other sector chapters; in certain cases, it is also necessary to reconcile carbon-stock estimates between discrete datasets and estimation methods (e.g., reconciling forest soil carbon estimates and cropland soil carbon estimates for land-use change from forestland to cropland).

The methods for quantifying GHG flux from land-use change are intended for use on lands managed to enhance the production of food, feed, fiber, and renewable energy. Methods are currently not provided for estimating emissions from energy used when converting land use from one category to another. Nor are methods provided for land-use change from settlements or the "other land" category to cropland, grazing land, wetland, or forestland.

Which Estimation Methods To Use?

Follow the methods in **Chapter 7: Land-Use Change** if you have changed land use in the past year and the land use changed from one to another of the following categories:

- Forest land
- Cropland
- Grazing land
- Wetlands

1.4 General Description of Available Tools and Methods

A landowner or manager can use several approaches to estimate GHG emissions at an entity scale. Each one gives varying accuracy and precision. The most accurate way to estimate emissions is direct measurement, which often requires expensive equipment or techniques that are not feasible for a single landowner or manager. On the other hand, lookup tables and estimation equations alone often do not adequately represent local variability or local conditions. This report seeks to provide methods that balance user-friendliness, data requirements, and scientific rigor in a transparent and justifiable way.

The following approaches were considered for these guidelines:

Box 1-10. Definitions: Activity Data, Emission Factor, and Ancillary Data

- **Activity data** include data on the magnitude of a human activity resulting in emissions or removals taking place during a given period.
- An **emission factor** is a coefficient that quantifies the emissions or removals of a gas per unit of activity.
- **Ancillary data** are additional data needed to support the selection of activity data and emission factors for the estimation and characterization of emissions.

Source: IPCC, 2019.

- **Basic estimation equations** combine activity data with parameters and default emission factors. Default parameters or emission factors (e.g., lookup tables) are provided in the text or an accompanying appendix. Emission factors are derived from models or available measurement data. See box 1-10 for background.
- **Models** also use combinations of activity data with parameters and default emission factors. Their inputs can be ancillary data (e.g., temperature, precipitation, elevation, and soil nutrient levels that may be pulled from an underlying source), biological variables (e.g., plant diversity), or site-specific data (e.g., number of acres, number of animals). A model's accuracy depends on the robustness of the model and the accuracy of the inputs.
- **Field measurements** are actual measurements that a farmer or landowner would need to take of the soil, forest, or farm to estimate actual emissions. Soil sampling to monitor carbon is one example of field measurement. Measuring actual emissions may require special equipment that monitors the flow of gases from the source into the atmosphere, such as remote sensing equipment (and applicable underlying micrometeorological methods). This equipment is not always readily available, so field measurements are more often incorporated into other methods to create a hybrid approach. For example, a field measurement, such as a sample mean tree diameter, could be incorporated into other models or equations to give a more accurate input.
- **Inference** uses State, regional, or national factors that approximate emissions/sequestration per unit of the input. The input data are then multiplied by this factor to determine the total onsite emissions. This factor can have varying degrees of accuracy and often does not capture the mitigation practices on the farm or the unique soil conditions, climate, livestock diet, livestock genetics, or any farm-specific characteristics, unless the factors are developed with specific soil types, livestock categories, climatic regions, etc.
- **Hybrid estimation approaches** combine the approaches described above. Hybrid approaches often use field measurements or models to generate inputs used for an inference-based approach to improve the estimate accuracy.

1.4.1 Selection of Most Appropriate Method and Management Practices to Include

This revised report reflects the current state of the science to include new methods and data sources. Specific updates to the methods are provided in the chapters and documented in table ES-1.

In drafting the methods for this report, the authors considered several selection criteria:

- **Transparency.** The assumptions and methodologies should be clearly explained to help users replicate calculations. Transparency of inventories is fundamental to the success of the process for the communication and consideration of information (UNFCCC, 2000).
- **Accuracy.** Estimates should be accurate in the sense that they are systematically neither over nor under true emissions or removals, as far as can be judged, and that uncertainties are reduced as far as practicable (UNFCCC, 2000).
- **Consistency.** The methods used to generate inventory estimates should be internally consistent in all their elements and the estimates should be as consistent with the original methods as the science allows. Consistency is an important consideration in merging differing estimation techniques from diverse technologies and management practices.
- **Comparability.** For the methods to be comparable, the estimates of emissions and sequestration being reported by one entity must be comparable to the estimates being reported by others (UNFCCC, 2000). Consequently, in general, the methods specify one method for any technology or management practice (i.e., users do not choose from a menu of methods). In some cases, the authors provided separate methodologies only to allow users to estimate emissions based on differing levels of detail for input data.
- **Completeness.** The methods must account for all sources and sinks, as well as all GHGs to the greatest extent possible. Completeness also means full coverage of sources and sinks under the control of the entity. Completeness is an important consideration to be balanced with ease of use in reporting appropriately for an entity that may have a minor activity or an activity with severely limited data availability (UNFCCC, 2000).
- **Cost-effectiveness.** The costs and benefits of additional efforts to improve inventory estimates or reduce uncertainty must be weighed against the efforts’ benefits. For example, there is a balance between the costs and benefits of additional efforts to reduce uncertainty.
- **Ease of use.** The user interface and underlying data requirements must not be impractically complex.

The authors evaluated updated sources to reflect current science, including the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Any IPCC methods that are used in this report are classified according to the system of methodological tiers developed by the IPCC, which is based on the complexity of different approaches for estimating GHG emissions (see box 1-11).

The methods range from the simple Tier 1 approaches to the most complex Tier 3 approaches. Higher tier methods, particularly Tier 3 methods, are expected to reduce uncertainties in the emission estimates if sufficient activity data are available and the methods are well developed and calibrated as demonstrated with adequate testing (IPCC, 2019).

Box 1-11. IPCC Tiers

- Tier 1 represents the simplest methods, using default equations and emission factors provided in the IPCC guidance.
- Tier 2 uses default methods, but emission factors that are specific to different regions.
- Tier 3 uses country-specific estimation methods, such as a process-based model.

The report authors used the following selection criteria in confirming or updating management practice to include the methods:

- The science reflects a mechanistic understanding of the practice's influence on an emission source.
- Published research (including international studies involving management, climate, and soils similar to those in the United States) supports a reasonable level of repeatability and consistency, and the response of emissions to the given practice is understood and quantifiable.
- The authors agreed the exclusion of this method would make the sector incomplete and there is strong enough evidence that the method will hold up for this practice for at least the next 5 years.

Some practices did not fulfill these criteria, and those practices were cited as areas that need more research. These research gaps are intended to become priority focus areas for agriculture and forestry climate change research by USDA, nongovernmental organizations, universities, and other research institutions.

1.4.2 Uncertainty

Limitations and data gaps exist in the methods to estimate emissions at the entity scale. The uncertainty range for each GHG estimate communicates the level of confidence that the estimate reflects the true GHG emissions or removal between the biosphere and the atmosphere. The uncertainty associated with GHG emissions and reductions estimates may have important implications for farmer and landowner decision making; in particular, a farm, ranch, or forest landowner or manager may be more inclined to invest in management practices that reduce net GHG emissions if the uncertainty range for an estimate is low, meaning higher confidence in the estimate. As new data become available and methods are developed, the uncertainty in emissions estimates will decline.

This report includes approaches for quantifying uncertainty in the estimated net emissions for each method. In general, a Monte Carlo approach (see chapter 8) should be used to estimate the uncertainty for the methods; it is currently the most comprehensive approach. Monte Carlo analyses require the use of statistical techniques to produce prediction intervals (i.e., the probability density function, or PDF) for the GHG emissions estimate.

The report also describes uncertainty assessment methods for each source as well as for the total estimate. Not all methods allow for a reliable statistical estimate of uncertainty due to a lack of data. In some cases, the authors used expert judgment to delineate estimated uncertainty bounds. In other cases, the report simply notes that more data are needed to reliably estimate uncertainty.

1.5 Chapter 1 References

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